



Study on the radiation flux and temperature distributions of the concentrator–receiver system in a solar dish/Stirling power facility

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ABSTRACT

Uniform heater temperature and high optical–thermal efficiency are crucial for the reliable and economical operation of a Solar Dish/Stirling engine facility. The Monte-Carlo ray-tracing method is utilized to predict the radiation flux distributions of the concentrator–receiver system. The ray-tracing method is first validated by experiment, then the radiation flux profiles on the solar receiver surface for faceted real concentrator and ideal paraboloidal concentrator, irradiated by Xe-arc lamps and real sun, for different aperture positions and receiver shapes are analyzed, respectively. The resulted radiation flux profiles are subsequently transferred to a CFD code as boundary conditions to numerically simulate the fluid flow and conjugate heat transfer in the receiver cavity by coupling the radiation, natural convection and heat conduction together, and the CFD method is also validated through experiment. The results indicate that a faceted concentrator in combination with a solar simulator composed of 12 Xe-arc lamps is advantageous to drive the solar Stirling engine for all-weather indoor tests. Based on the simulation results, a solar receiver-Stirling heater configuration is designed to achieve a considerably uniform temperature distribution on the heater head tubes while maintaining a high efficiency of 60.7%.

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1. Introduction

With the ever-increasing double pressure from energy crisis and environmental protection, the utilization of Solar Dish/Stirling technology in power generation attracts more attention of world-wide researchers. In order to reach the maximum possible engine efficiency and to ensure reliable operation with long life-span, it is favorable to allow the heater head of the Stirling Engine working under uniform high temperature that is close to the metallurgical point of the heater tube material. Therefore it is necessary to accurately predict the radiation flux and temperature distributions on the tube walls of the Stirling Engine heater head through a theoretical method, which will provide important guidance for the design of the solar energy collection system in the power generating facility.

The Monte-Carlo ray-tracing method is widely used in the field of solar energy utilization to analyze the ray propagation process and to determine the optical energy distribution [1–23]. Steinfeld et al. [1] investigated the influence of sunshape on the optimal parameters of a cavity receiver with a paraboloidal concentrator by

using the Monte-Carlo ray-tracing method. Sootha and Negi [2] presents a comparative study of the optical designs and solar flux concentrating characteristics of two designs of the linear Fresnel reflector solar concentrator (LFRSC) for the tubular absorber configuration, then the distribution of the local concentration ratio (LCR) on the surface of the tubular absorber were determined using the ray trace technique. Spirkel et al. [4] investigated the non-axisymmetric reflectors concentrating radiation from an asymmetric heliostat field onto a circular absorber for locations at higher latitudes. From the shape of the edge ray reflectors constructed for rays in the central south–north plane they found that a skew cone reflector might be appropriate for the field, and optimize its free parameters by means of ray-tracing. Pancotti [10] developed an optimized reverse ray-tracing model for flat mirror solar concentrators to obtain the irradiance distribution on the absorber, which allows reducing the noise and the necessary computing time. Shuai et al. [14] used the Monte-Carlo ray-tracing method to predict radiation performance of dish solar concentrator-cavity receiver systems, in which the effects of sunshape and surface slope error were taken into account. Based on the concept of equivalent radiation flux, they proposed an upside-down pear cavity receiver in view of directional attributes of focal flux. Villafán-Vidales et al. [17] numerically simulated the radiative heat transfer in a solar thermochemical reactor for the thermal reduction of cerium oxide by

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carrying out a Monte-Carlo ray-tracing method. Riveros-Rosas et al. [21] designed a new high radiative flux solar furnace with an intercepted power of 30 kW and a target peak concentration above 10,000 suns based on ray-tracing simulations. The design considers the concentrated radiative flux distributions, economical and other practical conditions. The directional characteristics and the power distribution of the concentrated solar radiation that enters the cavity were obtained for a paraboloidal concentrator. From the simulations, the aperture radius and the particle concentration were optimized to match the characteristics of the considered concentrator.

The coupled fluid flow and heat transfer problem have been studied by many researchers [24–34]. Ma [24] performed a series of tests to determine the convective heat loss characteristics of a cavity receiver for a paraboloid dish solar collector for various tilt angles and wind speeds. Reynolds et al. [26] numerically investigated the coupled flow and heat transfer in a trapezoidal cavity receiver containing steam tubes by using the CFD code FLUENT, and validated the numerical results through flow field visualization technique. Using FLUENT, Pérez-Rábago et al. [28] numerically studied the coupled conductive, convective and radiative heat transfer process in a special calorimeter of conical cavity named CAVICAL used to measure the thermal power of a point focus solar concentrator system. The analysis gave thermal losses and measured the thermal efficiency of the device. Reddy and Kumar [30] numerically studied the two-dimensional combined laminar natural convection and surface radiation heat transfer in a modified cavity receiver with solar parabolic dish collector using the CFD code FLLUENT. S2S model is chosen as the radiation model and coupled with the laminar natural convection model, in which the absorption, emission, and scattering of radiation by the working fluid were not considered. Isothermal boundary condition was given to the inner receiver walls. The influence of operating temperature, emissivity of the surface, orientation and the geometry on the total heat loss from the receiver is investigated. Kumar and Reddy [31] conducted numerical simulations to analyze the natural convective heat loss from three types of receivers for a fuzzy focal solar dish concentrator, namely cavity receiver, semi-cavity receiver and modified cavity receiver using FLUENT. They concluded that the modified cavity receiver experiences lower convection heat losses than the other receivers and is preferred for a fuzzy focal solar dish collector system. They also discussed the effect of receiver orientation on the natural convection heat loss in detail. Prakash et al. [33] carried out numerical study of the steady-state convective losses occurring from a downward facing cylindrical cavity receiver using the CFD code FLUENT. Different fluid inlet temperatures, different receiver inclination angles and different wind velocity were discussed, and their experiment on the convective heat loss validated the numerical results. Prakash et al. [34] carried out experimental and CFD studies to identify the stagnation and convective zones in a downward facing cylindrical solar cavity receiver, which is meant for providing low and medium temperature (50–150 °C) process heat.

The prior studies paid much attention to the analysis of various heat loss terms (conduction, convection and radiation) of the solar receivers since the optical–thermal energy conversion efficiency is a major concern for low and medium temperature utilization of the solar energy. However, for the high temperature usage of the solar thermal energy, especially for the Dish/Stirling technology, the temperature uniformity is equally important as the thermal efficiency issue, in other words, the receiver head is expected to bear a high and uniform temperature field, which is beneficial for the efficiency, reliability and life-span of the Stirling engine. In this paper, a Monte-Carlo ray-tracing method is applied to determine the radiation flux distribution on the receiver surface for various

concentrator–receiver combinations. The difference between the ideal paraboloid concentrator and the faceted real concentrator, the difference between the real sun and the solar simulator composed of multiple xenon lamps, the influence of different receiver positions, and the effects of different receiver shapes are discussed. The radiation flux profiles obtained from ray-tracing simulation are subsequently transferred to the CFD model as boundary conditions to numerically simulate the fluid flow and heat transfer in the receivers, thus the detailed temperature fields in the receivers can be determined. Both the ray-tracing method and the CFD code are validated through indoor experiments in advance using Xenon lamps as a solar simulator. Based on the simulation results, a new design of receiver assembly containing the heater tubes of a Stirling Engine with uniform temperature distribution and reasonably high optical–thermal conversion efficiency is presented.

2. Radiation flux distribution codetermined by the solar concentrator and the receiver

2.1. Validation of the ray-tracing code

The Monte-Carlo ray-tracing methodology replicates the real photon interactions, in which stochastic paths of a large number of rays are followed as they interact with surfaces. What happens to each of these rays depends on the emissive, reflection, and absorptive behavior in the surface, which is described by a set of statistical relationships. Accuracy increases with the number of rays traced and larger ray numbers means more processing time.

Although the optical software Tracepro® is a long-tested commercial ray-tracing code [35,36], simulations are carried out to compare with our own experimental data. As shown in Fig. 1(a), the experimental installation consists of a Xe-arc lamp with an electrical power of 7 kW combined with an ellipsoidal specular reflector, a cavity-type receiver with high-absorptivity placed shortly after the focal plane, and an irradiance flux measuring apparatus based on the optical–thermal–electrical conversion principle. The radiation beam produced from a Xe-arc lamp has a spectral distribution approaching that of the solar spectrum [37]. The 5 mm-thick borosilicate glass reflector has a shape of truncated ellipsoid of revolution with a semimajor axis of 429 mm, a semiminor axis of 215.4 mm, an aperture diameter of 365 mm and a hole diameter of 90 mm (at the rear end), and is silver-coated with a specular reflectance of 0.95 over the 0.28–2.5 μm spectrum. The concentrated beam passes through a diaphragm and reaches the receiver surface. The receiver surface is cavity-shaped and coated with special material having a high-absorptivity over the full spectrum, so the aperture of the receiver can be considered as a black-body surface. The radiation flux leads to a temperature gradient, which is converted into electrical signals through a thermopile, then magnified and collected by the data acquisition device, and finally displayed as radiation flux values.

In the ray-tracing model, the Xe-arc is simplified as a sphere surface light source with a diameter of 8 mm. The reflectance of the reflector is 0.95 for the full spectrum. The anode, cathode, the quartz bulb, the wire and the other details are just omitted (treated as completely transparent). The receiver aperture is modeled as a black-body circular plate. One million rays are used to start from the sphere surface and are traced through the system. The sampled ray display is shown in Fig. 1(b). The comparison between the experimental data and the ray-tracing results are shown in Fig. 1(c) and (d). The maximum measured radiation flux is 26.8 W/cm² and 35.6 W/cm², respectively for the two cases, only 2.9% and 6.6% lower than the corresponding ray-tracing results. The total received radiation power calculated from the ray-tracing results is only 0.21% and 0.32% higher than the corresponding experimental data

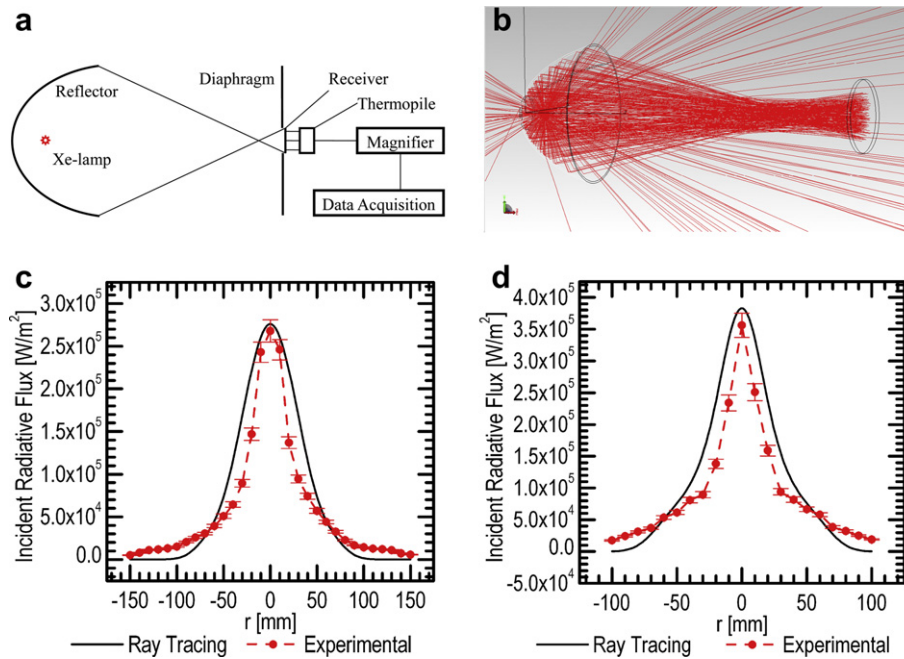


Fig. 1. Comparison of the ray-tracing results with the experimental data. (a) Schematic of the Experimental setup; (b) Sampled ray display generated from the ray-tracing results; (c) Comparison of results when the receiver aperture ($\Phi 300$ mm) is 270 mm after the focal plane; (d) Comparison of results when the receiver aperture ($\Phi 200$ mm) is 180 mm after the focal plane.

for the two cases, although the radiation flux profiles calculated from the ray-tracing deviate evidently from the experimental data. The major cause of discrepancy comes from the assumption of the shape and size of the Xe-arc, which is difficult to determine. The other important source of error comes from the neglect of the anode, cathode, the quartz bulb, the wire and other geometrical details whose complicated optical properties are difficult to accurately model. Other error-inducing factors include the heat loss and the precision of the measuring apparatus. In view of all these simplifications, the ray-tracing results agree reasonably well with the experimental data.

2.2. Comparison between the Xe-lamp solar simulator and the real sun

In order to overcome the limitations of weather, time and geographical conditions in our experiments, a solar simulator composed of multiple Xe-arc lamps are designed and fabricated in our laboratory. The light source is an array of 12 Xe-arc lamps arranged in two imaginary concentric circles with diameters of 4 m and 6 m, respectively. The lamps are uniformly spaced from each other in the circumferential direction, and are also configured so that the reflected rays from the concentrator do not intercept any lamp components. The receiver aperture is placed 190 mm after the

focal plane of the faceted real concentrator. Therefore a comparison of the concentrated radiation flux on the receiver surface is necessary to judge if the solar simulator is an effective substitute for the real sun. Ray-tracing simulation are performed on 64-bit Win7 PC platform with 2 CPUs and 4G memory, using 2.4 million initial rays for each case (the number of rays has been testified for “number independence”, in other words, the resulted total radiation power changes less than 1% if the ray number is further increased). Sampled ray display obtained from the ray-tracing results is shown in Fig. 2(a) and (b) for the 12 lamps case and real sun case, respectively. A standard solar irradiation flux of 1000 W/m^2 is assumed, and a half angle of 4.65 mrad is considered for the sunshape effect, while all the other conditions are kept the same as that of the xenon lamps case. Fig. 3(a)–(c) show the radiation flux contours on the receiver aperture plane. In the illustrated 6 lamps case, only 6 lamps at the outer circle participate in the ray-tracing process while 6 lamps at the inner circle are treated as completely transparent. The quantities in these figures are normalized in terms of their respective maximum flux values for the convenience of comparison. It is evident that the contours for the 12 lamps case are closer to that of the real sun case than that of the 6 lamps case, while the contours for the 6 lamps case are somewhat asymmetric. Therefore 12 Xenon-arc lamps are preferred in our experimental solar simulator installation, in which case the total incident

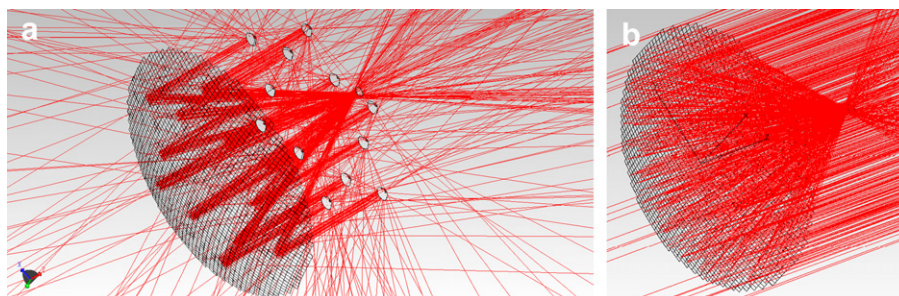


Fig. 2. Comparison between the solar simulator and the real sun. (a) Sampled ray display for the 12 Xe-arc lamps case; (b) Sampled ray display for the real sun case.

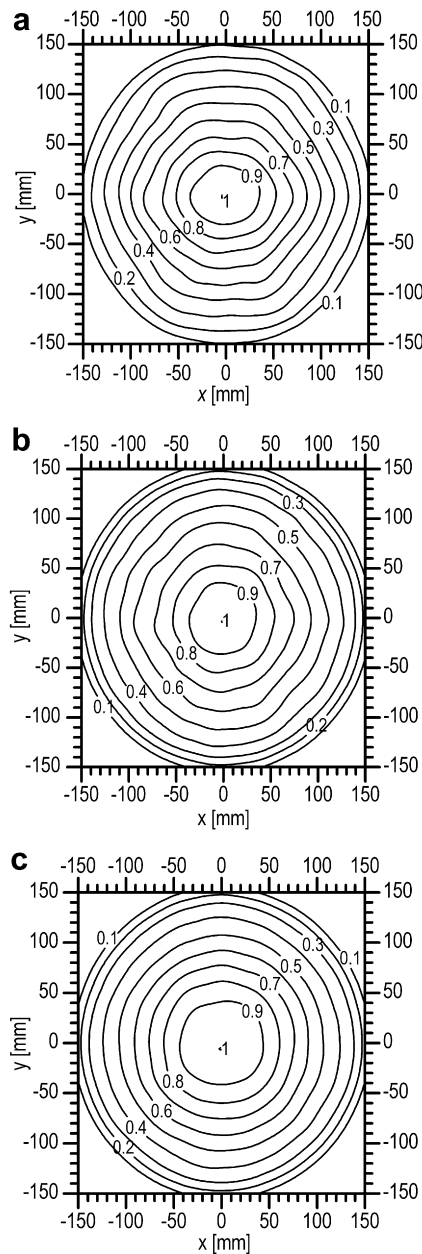


Fig. 3. Contours of normalized radiation flux at the receiver aperture plane (local radiation flux/maximum radiation flux in the plane) for (a) the 6 Lamps case; (b) the 12 Lamps case; and (c) the real sun case.

radiation power at the receiver aperture reaches 12,554 W, which is adequate for driving a solar Stirling engine.

2.3. Comparison between the faceted real concentrator and the ideal paraboloidal concentrator

A real solar concentrator composed of 2136 silver-coated flat-mirror facets, each having a square shape of $150 \times 150 \text{ mm}^2$, combined to approximate the shape of an ideal paraboloid of revolution with an aperture diameter of 8 m and a focal length of 5.8 m, is built in our indoor experimental facility. Thus it is necessary to make an investigation on the effects caused by a faceted real concentrator in comparison with that resulted from an ideal concentrator.

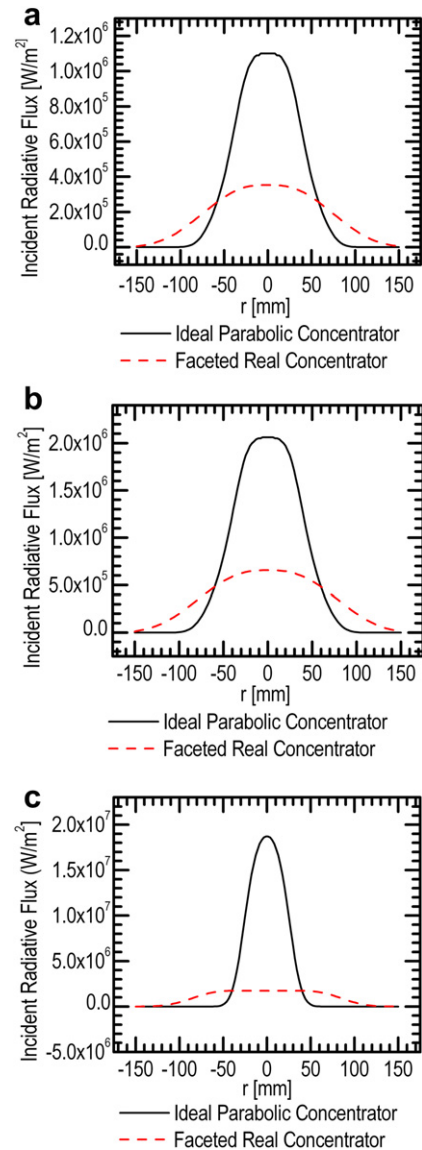


Fig. 4. Comparison of the radiative flux distribution between the real concentrator and the ideal paraboloidal concentrator for (a) the 6 lamps case; (b) the 12 lamps case; and (c) the real sun case.

The shape, size, position and orientation of each of the 2136 flat-mirror facets is modeled by the Pro/Engineer Wildfire® V2.0 software, and is subsequently transferred to the ray-tracing code Tracepro® V4.1.6 via an intermediate ACIS format. Ray-tracing simulation is performed for the faceted real concentrator and the corresponding ideal paraboloidal concentrator, respectively. Fig. 4 illustrates the radiative flux profiles in the focal plane for the faceted real concentrator in comparison with that of the ideal paraboloidal concentrator for the 6 lamps case, the 12 lamps case and the real sun case, respectively. 2.4 million initial rays are used for each simulation.

As can be inferred from Fig. 4(a)–(c), the faceted real concentrator will collect almost the same amount of energy as the ideal paraboloidal concentrator. For examples, for the 6 lamps case (Fig. 4 (a)), the total incident irradiance power in the 300-mm-diameter receiver aperture is 8044 W for the ideal concentrator and 8008 W for the faceted real concentrator, with a difference of only 0.45%; for the 12 lamps case (Fig. 4(b)), the total incident irradiance power in the 300-mm-diameter receiver aperture is 16,102 W for the ideal

concentrator and 15,980 W for the faceted real concentrator, with a difference of only 0.76%; and for the real sun case (Fig. 4(c)), the total incident irradiance power in the 300-mm-diameter receiver aperture is 45,191 W for the ideal concentrator and 43,040 W for the faceted real concentrator, with a difference of only 4.76%. It can be seen from the figures that a more uniform distribution of radiation flux can be realized by the faceted real concentrator due to the blurring effects of the large quantity of small flat mirrors. This is evidently beneficial for the application to a solar Stirling engine. The faceted real concentrator has evident advantages over the ideal parabolic concentrator in that the maximum heat flux and the maximum temperature in the heater tubes are significantly reduced, local overheating damage is avoided and the engine life-span is significantly increased, the whole heater assembly is subject to a more uniform thermal load and more uniform high temperature, and the engine system may achieve a higher thermal-mechanical conversion efficiency according to the thermodynamic

theory. In addition, the faceted concentrator has a considerably lower manufacturing cost than the ideal paraboloidal concentrator.

2.4. Effect of the receiver location on the radiative flux distribution

A series of ray-tracing simulations are performed to investigate the effects of receiver position relative to the concentrator focal plane on the radiation flux profile and the optical power collecting efficiency of the concentrator–receiver system. The optical power collecting efficiency is defined as the total incident radiation power within the $\Phi 300$ mm receiver aperture divided by the total radiation power carried by all the initial rays starting from the above-mentioned Xe-arcs or a circular solar source with a diameter of 8 m. Fig. 5(a)–(d) shows the incident radiation flux profiles in the receiver apertures for different receiver locations. The figures indicate that either for Xe-arc lamps or for the real sun, the incident radiative flux is the sharpest, i.e. the most non-uniform at the focal

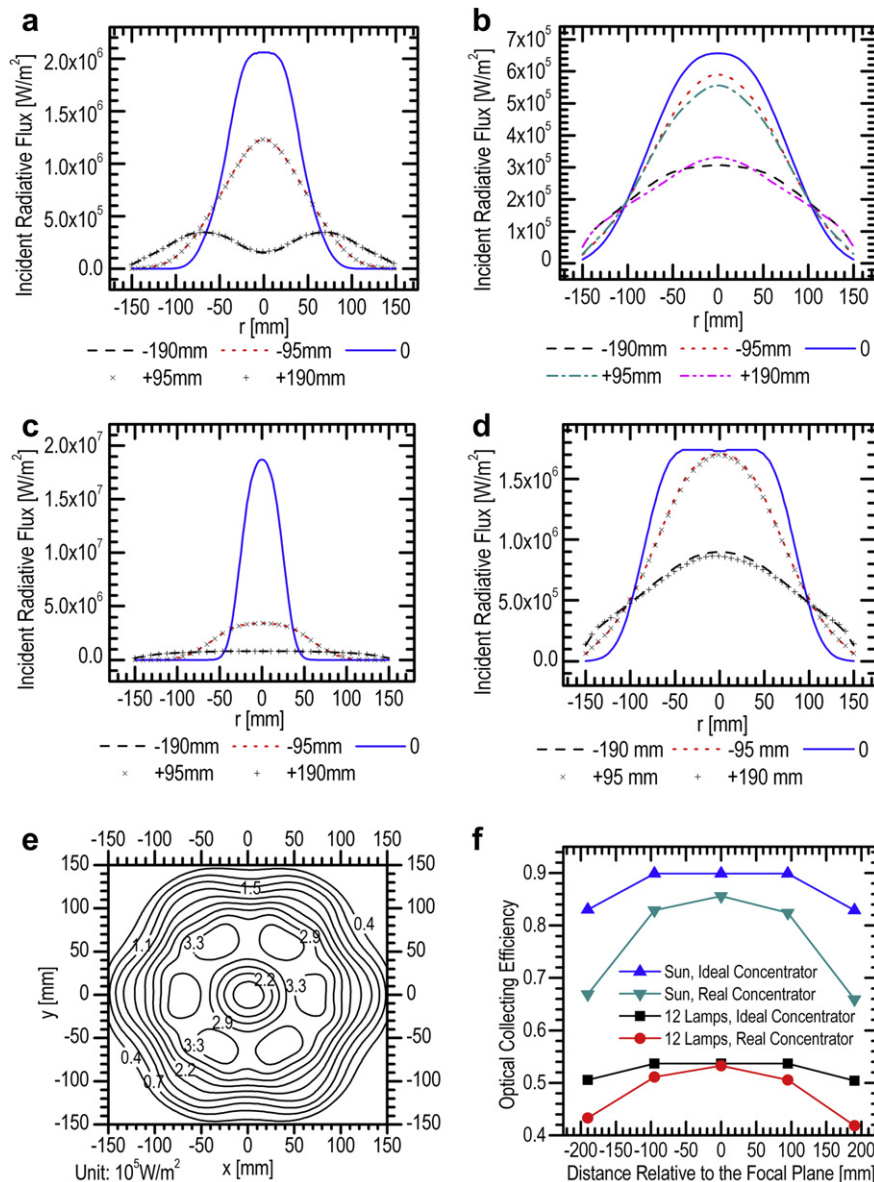


Fig. 5. Effect of the receiver position on the radiation flux distribution and radiation collecting efficiency. (a) Radiative flux profiles for the 12 Xe-arc lamps, ideal paraboloidal concentrator case; (b) Radiative flux profiles for the 12 Xe-arc lamps, faceted real concentrator case; (c) Radiative flux profiles for the real sun, ideal paraboloidal concentrator case; (d) Radiative flux profiles for the real sun, faceted real concentrator case, with the signs “+” and “-” in the distance values indicating the position of the receiver aperture being after or before the concentrator focal plane; (e) Radiation flux contours in the receiver aperture for the +190 mm case in Fig. 5(a); (f) Radiation collecting efficiency for (a)–(d) cases.

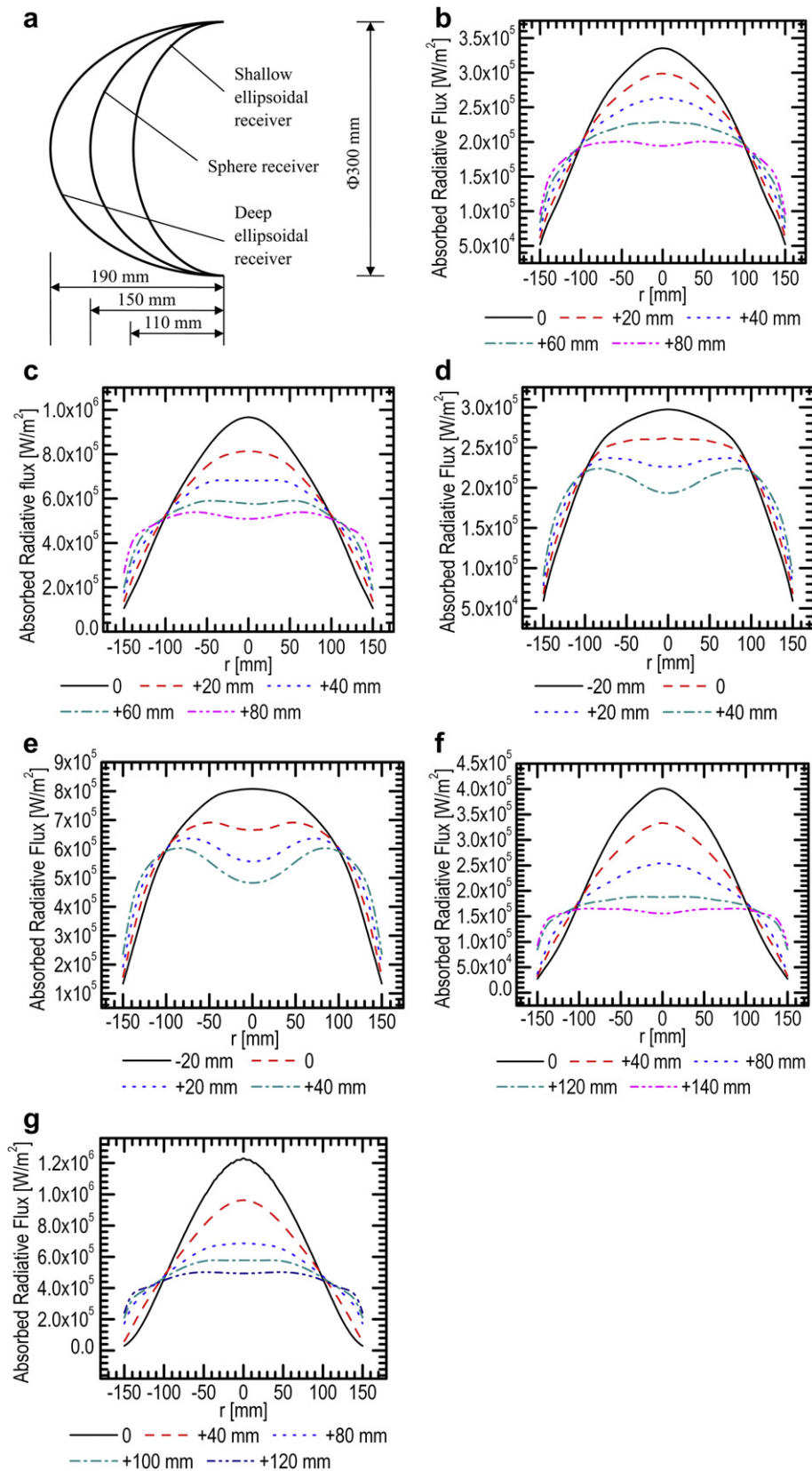


Fig. 6. Influence of different receiver shapes on the radiation flux distribution. (a) Schematic of the three receiver shapes; (b) Hemisphere receiver, 12 Xe-arc lamps case; (c) Hemisphere receiver, real sun case; (d) Deep semi-ellipsoidal receiver, 12 Xe-arc lamps case; (e) Deep semi-ellipsoidal receiver, real sun case; (f) Shallow semi-ellipsoidal receiver, 12 Xe-arc lamps case; (g) Shallow semi-ellipsoidal receiver, real sun case.

plane position. When the receiver moves away from the focal plane either in positive or in negative direction, the radiative flux profile tends to be flattened, i.e. more uniform. Also, the faceted real concentrator results in a more uniform radiative flux distribution compared to the ideal paraboloidal concentrator due to the blurring effects of the large amount of small flat-mirror facets, reducing the peak radiation flux, as explained before. The simulation results for different concentrator–receiver combinations provide a basis for the design optimization of the concentrator–receiver system.

Fig. 5(e) illustrates the asymmetric pattern of the radiative flux distribution for the “+190 mm” case in Fig. 5(a). This figure is used to explain that the maximum radiation flux may not necessarily occur at the receiver center when the receiver is moved a distance away from the focal plane in the positive direction, but may occur somewhere at a circle around the center due to the ray divergence effect after the focusing point. It should be noted that the profiles in Fig. 5(a)–(d) are averaged in the circumferential direction.

Fig. 5(f) shows the collecting efficiency of radiation power at different receiver locations for the Fig. 5(a)–(d) cases. The collecting efficiency is the highest when the receiver is placed at the focal plane, and decreases when the receiver moves forward or backward relative to the focal plane. The collecting efficiency of the Xe-arc lamps cases is significantly lower than that of the real sun cases because a large amount of rays leak out of the system from the front opening and the rear hole of the lamp reflector. The faceted real concentrator collects less radiation power than the ideal paraboloidal concentrator due to its poorer focusing ability, so more rays are reflected out of the system, leading to slightly lower collecting efficiency.

2.5. Effect of the receiver shapes on the radiative flux distribution

The receiver shape functions to redistribute the incident radiation energy, therefore has significant influence on the final heat flux distribution on the heater tubes of the Stirling engine. A series of ray-tracing simulations are performed for 3 receiver shapes with an equal aperture size of $\Phi 300$ mm in this study. One is a hemisphere receiver with a depth or radius of 150 mm, the other is a deep semi-ellipsoidal receiver with a depth or semimajor axis of 190 mm, and another is a shallow semi-ellipsoidal receiver with a depth or semimajor axis of 110 mm, as shown schematically in Fig. 6(a). The same faceted real concentrator are used for all cases, the absorptance of the receiver surface are 0.75, and all the other parameters and conditions are kept the same for the three different shapes. Fig. 6(b)–(g) show the profiles of the absorbed radiation flux on the receiver surface for three different receiver shapes when the receivers are paced at different locations relative

to the concentrator focal plane for the 12 Xe-arc lamps case and for the real sun case, respectively. The results reveal that it is the easiest to obtain a uniform flux distribution by the shallow semi-ellipsoidal receiver, the next is by the hemisphere receiver, and the most difficult is by the deep semi-ellipsoidal receiver. In all cases, the radiation flux tends to be more uniform when the receiver moves away some distance from the concentrator focal plane although the efficiency may sacrifice a little. The radiation flux profiles have a similar pattern for both the 12 Xe-arc lamp case and the real sun case. When the 12 lamp solar simulator is used, the radiation collecting efficiency of the concentrator–receiver system for the illustrated receiver locations is 0.431–0.438 for the hemisphere receiver, 0.466–0.469 for the deep semi-ellipsoidal receiver, and 0.376–0.412 for the shallow semi-ellipsoidal receiver. When real sun is used, the corresponding efficiency is 0.686–0.698 for the hemisphere receiver, 0.740–0.749 for the deep semi-ellipsoidal receiver, and 0.622–0.647 for the shallow semi-ellipsoidal receiver. The higher efficiency of the deeper cavity receiver can easily be explained by the multiple reflections and multiple re-absorptions within the cavity.

3. Temperature distribution on the receiver surface

3.1. Validation of the CFD method and the radiation model

The final temperature distribution on the heater tubes of the Stirling engine is determined by the absorbed radiation flux and the heat transfer conditions in the receiver cavity. A commercial CFD code FLUENT 12.0 based on the Finite Volume (FV) method is used in this study to solve the coupled fluid flow and heat transfer problem by simultaneously taking into account the conduction, convection and radiation effects. Experiment is carried out to validate the numerical simulation method. The experimental system includes a solar simulator composed of 4 Xe-arc lamps with ellipsoidal reflectors, each having a light emitting power of 1.6 kW. The reflectors are configured to have a common focus, as shown in Fig. 7(a). A barrel shaped stainless steel receiver with a diameter of 300 mm and a height of 300 mm is positioned such that its aperture center is located at the common focus of the 4 ellipsoidal reflectors. The receiver loses heat to the environment through natural convection and radiation. It needs approximately 30 min to reach a heat balance. The steady-state temperature distribution on the barrel surface is measured by 28 thermocouples and a data acquisition device.

An imaginary air cylinder with a diameter of 900 mm and a height of 900 mm enclosing the receiver barrel is taken as the computational domain, which is large enough to take the natural

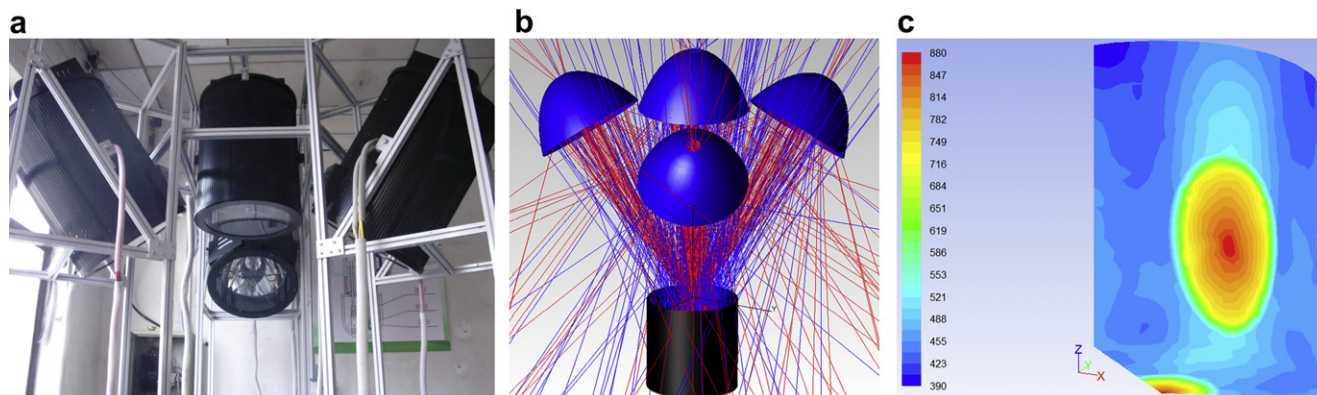


Fig. 7. Validation of the numerical method via experiment. (a) Configuration of the 4 Xe-arc lamps; (b) Sampled ray display from the ray-tracing results; (c) Calculated temperature distribution on the receiver surface.

Table 1

Comparison of temperature results between the experimental measurement and the numerical simulation.

Vertical distance from the barrel bottom (mm)	Number of measured points	$T_{\text{measured}} - T_{\text{calculated}}$ at the measured points
280	4	−2.3 to +3.2 K
200	6	−2.9 to +3.1 K
120	5	−3.7 to +4.4 K
60	4	−3.5 to +4.3 K
0	9	−4.4 to +4.7 K

convection around the receiver into account. Due to the rotationally periodical arrangement of the lamps, only 1/3 model of the domain is calculated, with a “Rotational Periodic” boundary condition applied to the cutting faces. “Pressure Inlet” and “Pressure Outlet” boundary conditions (ambient pressure) with emissivity of 1.0 are specified for the outermost boundaries of the computational domain. The receiver walls are treated as conductive “Thin Wall” with only conduction in the thickness direction being considered. The inner and outer surfaces of the receiver are considered gray surfaces with emissivity of 0.75. The implicit method is chosen to discretize the conservation equations of continuity, momentum and energy. The Second Order Upwind Scheme (SUS) is used for discretizing the convective terms in the momentum and energy conservation equations. The SIMPLEC algorithm is selected for the pressure–velocity coupling owing to its excellent converging efficiency. The Discrete Ordinate (DO) model is selected as the radiation model for its universal applicability, which is capable of dealing with specular and diffusive reflection, surface-to-surface radiation and radiative participating media, scattering media, particulate effect, gray and non-gray surfaces, radiation at semi-transparent walls, etc. In this study, the air is considered a radiation participating media, but the scattering and absorbing effects are neglected. Ideal gas model is selected for the air density. A grid size of 1.6 million cells is used based on a grid independence test. The calculated average temperature over the barrel surfaces varies less than 1 K when further increasing the grid size.

Ray-tracing simulation is performed using the same condition as the experiment. A sampled ray display from the ray-tracing results is shown in Fig. 7(b). The absorbed radiation flux of the receiver walls calculated from the ray-tracing results is applied to the receiver wall as a heat load through a “Profile” function in a discrete and interpolated manner. The calculated temperature distribution is shown in Fig. 7(c). A comparison of the temperature data between the calculation and the measurement is shown in Table 1. They agree quite well with a maximum deviation of 4.7 K.

3.2. A new receiver design based on the numerical simulation

As shown in Fig. 8(a), a new receiver design is presented in this paper based on the simulation results of Fig. 6(c). When the aperture of a hemisphere receiver is positioned 60 mm after the concentrator focal plane, it is expected to obtain substantially uniform heat flux and temperature distribution. The heat-absorbing stainless steel tubes with an absorptance of 0.75 are arranged to conform to the hemisphere as close as possible. The tubes have approximately equal lengths and diameters to gain a uniform pressure drop. The tubes are curved and densely configured in the radial and circumferential directions in order to fully and uniformly cover the hemisphere extension. Nevertheless, a small amount of rays may leak out to the outside of the hemisphere shaped tube layer, so a hemisphere shaped silver-coated reflector with a reflectance of 0.95 is designed to closely surround the heater tubes to reflect the small fraction of leaked radiation back to the tubes. A thin glass cover is designed to reduce the radiation and convection heat loss from the receiver aperture, while the concentrated solar energy is allowed to enter the receiver cavity.

The computational domain includes the air space enclosed by the glass cover, the reflector surface and the heater tube walls. The glass cover is modeled as a semitransparent wall that allows external irradiation flux entering the domain. The incident irradiation flux profile and the corresponding ray directions at the receiver aperture obtained from the ray-tracing procedure are input into the FLUENT code via a discrete and interpolated “Profile” function. Natural convection and radiation boundary condition is applied to the external side of the glass cover with a convective heat transfer coefficient of 10 W/(m² K), an environmental fluid temperature of 300 K and an external emissivity of 1.0. The tube walls are treated as conductive thin walls with only conduction in the thickness direction considered. Since the helium gas flow in the tubes is high-frequency oscillating, all the inner tube surfaces are considered to be subject to approximately uniform convective cooling by the helium gas, then a constant convective heat transfer coefficient of 500 W/(m² K) and a constant helium gas temperature of 900 K are specified for this side of the tube wall. The reflector surface is set as adiabatic wall with an internal reflectance of 0.95.

The implicit method, SUS scheme, the SIMPLEC algorithm, the DO radiation model and the ideal gas model are selected in the numerical simulation. A grid size of 4.9 million cells is used based on a grid independence test. The calculated average temperature over the barrel surfaces varies less than 2 K when further increasing the grid size. The simulation is performed on 64-bit Windows Server 2008 R2 platform using 8 CPUs and 12G memory. The calculated temperature distribution is shown in Fig. 8(b). The

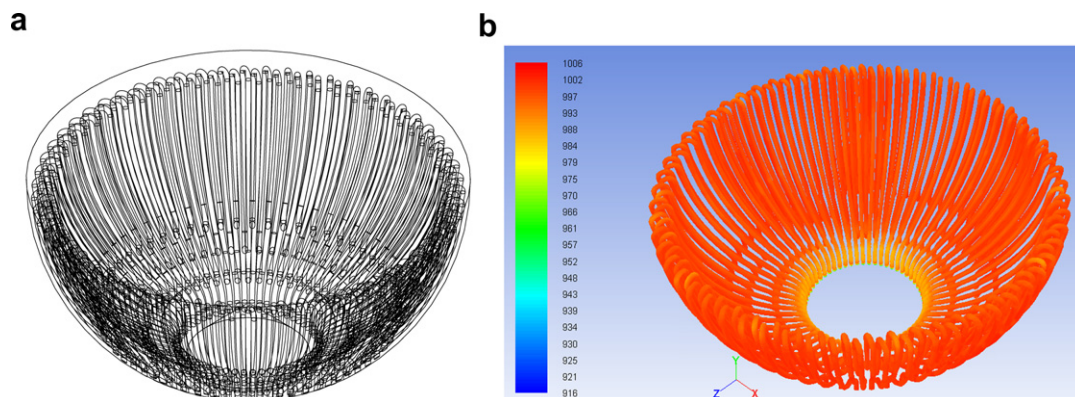


Fig. 8. Prediction of the temperature field of the new design receiver. (a) Schematic of the new receiver design; (b) Temperature distribution on the heater tubes of a solar Stirling engine.

temperature ranges from 981.3 to 1002.3 K over the air-side tube surfaces, the variation of which is less than 21 K, exhibiting a substantially uniform distribution, while the calculated overall optical–thermal efficiency of the concentrator–receiver system is up to 60.7% in this case.

4. Conclusion

The Monte-Carlo ray-tracing method and the CFD method are combined to investigate the radiation flux and temperature distributions of the concentrator–receiver system in a solar Dish/Stirling power facility. Both methods are validated by experiment. The following conclusions can be drawn from this study.

- (1) Substantially uniform radiation flux and temperature distributions can be realized by a faceted real concentrator due to the blurring effects of the large amount of small flat-mirror facets while the total collecting efficiency is only slightly lower than that of the ideal paraboloidal concentrator, which is beneficial for the long-term reliable and efficient operation of the Stirling engine. A total incident radiation power of 12,554 W at the receiver aperture with a flux pattern similar to that generated by the real sun can be achieved by a solar simulator composed of 12 pieces of 7 kW_e Xe-arc lamps, which is adequate to drive the solar Stirling engine for indoor experiment and is immune to the weather, time, and geological variations.
- (2) When the receiver moves forward or backward relative to the focal plane, the radiation flux tends to be more uniform, but the collecting efficiency decreases due to more leakage of rays. The simulation results for different concentrator–receiver combinations provide a basis for the design optimization of the concentrator–receiver system.
- (3) It is the easiest to obtain a uniform flux distribution by the shallow semi-ellipsoidal receiver, the next is by the hemisphere receiver, and the most difficult is by the deep semi-ellipsoidal receiver. However, the deep cavity receiver tends to possess a higher collecting efficiency due to the repeated reflection and re-absorption in the cavity.
- (4) A new solar receiver-Stirling heater configuration is designed based on the simulation results, in which the tubes are configured to closely conform to and fully occupy an imaginary hemispherical surface. The calculated temperature variation over the tube walls is less than 21 K, exhibiting a considerably uniform distribution, while the calculated overall optical–thermal efficiency of the concentrator–receiver system is up to 60.7%.

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